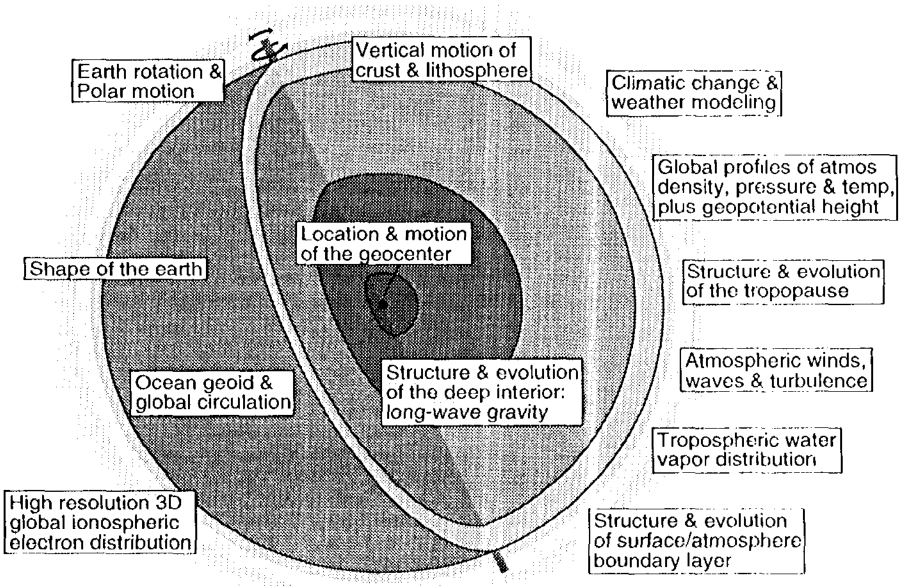
RECENT ACTIVITIES IN SPACEBORNE GPS

Thomas P. Yunck
The Jet Propulsion laboratory
California institute of Technology, Pasadena, CA 91109 USA

INTRODUCTION

After years of patient advocacy and paper studies by a diverse corps of enthusiasts, spaceborne GPS has at last become a presence in the real world of flight projects. Indeed, owing to rapidly declining hardware costs (some flight receivers are now well under $100K) and the high value of autonomous onboard positioning, timing, and attitude determination, basic navigation receivers are coming to be seen as almost indispensable to future low earth orbiters. Equally dramatic, and perhaps more surprising, is the strong emergence of direct spaceborne GPS science and the blossoming of new and unexpected science applications for high performance geodetic space receivers. (It is fortunate, in this era of continuous GPS anti-spoofing, that "codeless" L2 tracking techniques have matured to the point that they can meet even the most stringent science requirements.)

Science applications of spaceborne GPS include centimeter-level precise orbit determination (POD) to support ocean altimetry; Earth gravity model improvement and other enhancements to GPS geodesy; high resolution 3D ionospheric imaging; and atmospheric sounding (occultation) to produce precise profiles of atmospheric density, pressure, temperature, and water vapor distribution. Figure 1 offers a simplified graphical summary of the Earth science now emerging from spaceborne GPS.



Fig, 1. Some key science applications for a spaceborne array of GPS receivers.

There has thus developed a two-tiered user community for GPS in space: those seeking basic, moderate performance GPS navigation, timing, and (in some cases) attitude determination, and those pursuing more demanding science applications requiring the highest performance dual frequency receivers. As the mission-dependent requirements within each group are diverse, a variety of receiver models for space use has emerged. It may be hoped that within a few years, the high end instruments will have reached a level of miniaturization, low cost, and generality of function that they can economically serve both user classes, thereby converting the most utilitarian satellites into potentially powerful science instruments.

Here I will first review some recent highlights in the area of "utility GPS" in space, and then examine some of the more promising developments in the application of spaceborne GPS to Earth science.

ONBOARD POSITIONING AND ATTITUDE DETERMINATION

Conventional single and dual frequency GPS receivers have been flown in space for basic navigation and (increasingly) attitude determination on a number of recent missions. These include RADCAL, Christa-SPAS, Orbcomm, and MicroLab I, which carried the Trimble TANS Vector receiver for positioning and attitude determination; and several Space Shuttle flights, which carried a dual frequency Rockwell-Collins 3M receiver. A variant of the Rockwell receiver, the AST V, was flown on two U.S. military satellites, the Air Force's TAOS (Technology for Autonomous Operational Survivability) and the Advanced Research Projects Agency's experimental DARPASAT. in addition, a 12-channel, single frequency, P-code receiver built by Motorola was flown aboard NASA's Extreme Ultraviolet Explorer (EUVE), and a S-channel Japanese C/A-code receiver was flown on Japan's OREX mission.

The Trimble/Stanford/Loral Vector & Tensor

RADCAL is a U.S. Air Force satellite designed principally to calibrate C-band radars around the world. The Trimble TANS Vector receiver (originally the TANS Quadrex, which was modified in part by a group at Stanford University [Lightsey et al, 1994]) aboard RADCAL is a single-frequency C/A-code receiver which sequences rapidly through four separate antennas to obtain differential phase data for attitude determination while performing routine onboard position solutions. The Vector is the first attitude-capable receiver to fly in space, although it is not in the usual sense "space qualified." A more space-worthy commercial version of the Vector, known as the Tensor, is now under development by Space Systems Loral [Brock et ai, 1994]. **The** RADCAL attitude determination experiment was led by Glenn Lightsey of Goddard Space Flight Center (GSFC) and Clark Cohen of Stanford [Cohen et al, 1993]. They report attitude accuracies of better than 0.5° with a baseline of about 1 m between the antennas.

The TANS Vector was also flown aboard the Astro-SPAS platform, a telescope-bearing free flyer developed by the German space agency (DARA), which is released from the Space Shuttle to conduct observations and then retrieved. The "Christa" SPAS flight in November 1994 featured the first demonstration of real time GPS attitude determination on a space platform. The experiment was supported by the receiver group from Loral, which made software modifications to enable, among other things, satellite acquisition and operation from a cold start in space. Attitude accuracy was again estimated at a few tenths of a degree. The Vector has flown on several other missions including two Orbital Sciences Corporation Orbcomm satellites and the MicroLab 1 mission, all launched together on a single Pegasus in April 1995.

Future plans for the Vector include flights on GEMSTAR, to be orbited in July 1995 by a Lockheed launcher, with upgraded software designed to improve real time attitude accuracy; SPARTAN, snot her free flyer to be deployed by the Shut t le in November 1995, which will attempt the first real time closed loop attitude control solely with GPS [Bauer et al, 1994]; JAWSAT, under development for a 1996 launch by students and faculty at the U.S. Air Force Academy and Weber State University [Chesley and Axelrad, 1994]; and the Small Satellite Technology initiative (SSTI) "Clark" mission in 1996. The upgraded Loral Tensor will be flown on the SST1 "Lewis" mission and a later Astro - SPAS flight, both in 1996.

Other Recent Flight Tests

The Space Shuttle has carried a Rockwell-Collins 3M receiver on a number of recent flights to validate its utility for real time state determination, with typical SA-limited accuracies of -100 m in position and -1 m/s in velocity. The 3M (a version of the Rockwell Miniature Advanced GPS Receiver, or MAGR), is a 5-channel, dual frequency military receiver (four L1 channels and one sequencing L2 channel) modified for operat i on in Earth orbit. It will continue to be flown experimentally on future Shuttle missions. During a planned November 1996 Astro-SPAS flight, the co-orbiting Tensor (on the SPAS) and 3M (on the Shuttle) should afford the first demonstration of precise relative position ing with GPS in space. A decision was recently made to outfit all four Shuttle orbiters, which have long been equipped with twin, dual frequency GPS antennas (one on top, one on the bottom), with MAGRs for formal operational use. This will be accompl ished gradual 1 y, over the next few years. The plan is to combine! the outputs of the two antennas before feeding the signal into the receiver.

A dual frequency Rockwell AST V P-code receiver was adapted for flight on the U.S. Air Force's TAOS mission, launched in February 199410 evaluate autonomous navigation systems, and on DARPASAT, which was carried on Orbital Sciences Corporation's first Taurus launch in March 1994 [Cubbedge and Higbee, 1994]. The latter mission i nvolved a co] laborat ion bet ween ARPA, Rockwc] 1, B al I Aerospace, and the Air Force's Phillips Laboratory. The AST V [Sfeir and Weninger, 1991], which takes its name from ARPA's Advanced Satellite Technology program, is derived from the MAGR design and features six channels that track four satellites continuously while sequencing through all other visible satellites with the remaining two channels. It is capable of dual frequency P-code and C/A-code operation. Though both receivers have operated successfully, onboard power limitations on DARPASAT keep it off much of the time. in addition, nearly continuous GPS anti-spoofing since January 1994 has forced both receivers to operate primarily in their L1 C/A-only mode; since they are not SA-capable, onboard posit ion accuracies have been in the SO-100 m range. off-line different ial processing of the TAOS data has improved this to better than 3 m [Guinn et al, 1995]. 'l'he TAOS recei ver is no longer operat ional.

NASA's EUVE carries an unusual 12-channel, L1-onl y unit built by Motorola, which tracks the L1 P-codes when anti-spoofing is off and the C/A-codes otherwise. It produces continuous 1.1 carrier phase data in addition to pseudorange. The receiver is a modified version of the dual frequency Topex/Poseidon receiver, described in the next section. A group led by Ken Gold of the University of Colorado has carried out a variety of studies on EUVE exploring the potential accuracy of real time, single-frequency orbit solutions with an onboard Kalman filter, as well as precise after-the-fact differential solutions [Gold et al, 1994]. A notable aspect of that work is their experimentation with single-frequency ionospheric delay correction by averaging the phase and group delay (pseudo-range) observables. (EUVE orbits at S00 km and carries twin GPS antennas providing a full sky field of view down to the Earth limb; resulting ionospheric delays occasionally exceed 50 m.) That technique is known as GRAPHIC (GRoup And P} last Ionosphere Calibration), and is analogous to the DRVID (Differenced Range vs Integrated Doppler) technique demonstrated some years ago for deep space tracking [MacDoran, 1970]. The GRAPHIC data dramatically reduced post-fit residuals and consistently improved orbit solutions. Combining GRAPHIC data and reduced dynamic orbit estimation (discussed in more detail below), Gold achieved differential orbit solutions accurate about 1 m ('judged by orbit overlaps). Simulated real time (non-differential) solut ions were accurate to about 12 m (judged by agreement with the differential solutions) when selective availability was off, and about 15 m when it was on. The relatively small degradation from SA "dither" illustrates the power of smoothing with a real time Kalman filter.

Future Developments

A group at GSFC led by Tom Clark is devising another low cost C/A-code receiver for flight on the next AMSAT (the Amateur Radio Satellite Corp.) mission, known as P3D, scheduled for flight in 1996. The receiver is being assembled from the GEC Plessey "open architecture" GPS chip set and "GPS Builder" development system. It will take input from up to eight GPS antennas and perform onboard orbit and attitude determination and timing. **in** contrast with the TANS Vector and Loral Tensor, which perform rapid switching (time-multiplexing) among four antennas, the P3D receiver will dedicate a separate RF channel to each of the eight antennas. The receiver can track up to 24 signals (many of them redundant for attitude determination) from the multiple antennas. The development team hopes to fly the receiver on other satellites after AMSAT.

The most power-efficient GPS flight receivers today draw in the neighborhood of a few watts continuously, a level which can be burdensome for some microsat missions, which may have less than ten watts for all purposes. To address that issue, an innovative GPS experiment will be carried aboard a small student-led mission known as SNOE (Student Nitric Oxide Explorer), being developed at the University of Colorado (Contact: Prof. Charles Barth). SNOE is funded by NASA through the University Space Research Association and is planned for an early 1997 launch. It will carry an experimental, rudimentary "receiver" which will simply down-convert the L1 frequency to baseband and sample the raw spectrum at 2 MHz for periods of a few milliseconds. Sampling will take place only a few times each orbit. The sampled data will contain the signals from all visible GPS satellites; a processor will then extract C/A-code pseudorange measurements to be fed into a Kalman filter for orbit and clock estimation. Because the receiver will be on only briefly and infrequently, average power consumption will be less than 0.01 watts, with brief peaks of a few watts. Owing to the great strength of dynamic orbit estimation and the instantaneous GPS observing geometry, continuous real time orbit knowledge can remain accurate to the order of 200 m. For the SNOE flight, the GPS processing will be performed on the ground as a demonstration. Proposed later missions, including a Space Technology Research Vehicle sponsored by the Defence Research Agency in the UK [Wells, 1994], will carry out all processing onboard.

These represent just a sampling of current activities in spaceborne GPS positioning, att itude determination, and timing. Many other essential l y (by now) routine applications are in progress, including a number of overseas efforts [e. g., Tomita et al, 1994; Zielinski et al, 1994], and undoubtedly some important activities have been overlooked. A noteworthy next step will be the advent of dual GPS-GLONASS receivers for space (they're only now appearing for ground use, e.g., Balendra et al [1994]). As GLONASS becomes established as a reliable long-term navigation system we can expect to see considerably mom commercial resources devoted to developing the technology. A GPS-GLONASS receiver in space could appear within the next two years.

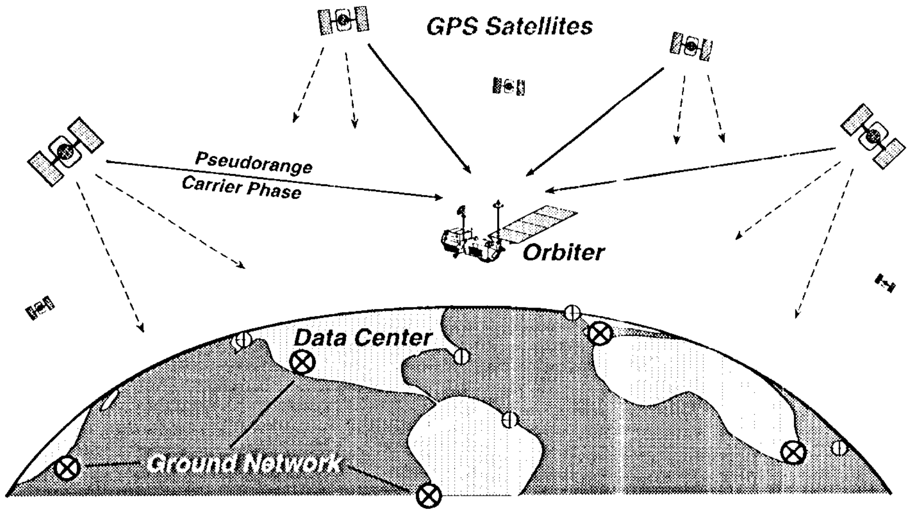


Fig. 2. Key system elements for precise orbit determination with differential GPS.

SPACEBORNE GPS FOR EARTH SCIENCE

The utilitarian spaceborne GPS applications catalogued in the previous section represent, in essence, a fulfillment of the GPS vision. They exploit GPS, sometimes in clever ways, for purposes for which is was explicitly intended. For the growing class of high-precision spaceborne science users surveyed here, the same cannot be said. GI'S was not conceived with such uses in mind (indeed, their feasibility was generally recognized only after GPS deployment was well underway), and has not been altered in any way to accommodate them. Within these diverse enterprises we find many examples in which GPS innovators have, through ingenuity and industry, coaxed a reluctant system to perform unexpected feats and thereby expand its mission. In the face of the seriously confounding security features known as selective availability and anti-spoofing, they have extracted from GPS levels of perform ante undreamed of by its architects. This section summarizes recent highlights in spaceborne GPS science and sketches a picture of its promising future.

Precise Orbit Determination and Gravity Improvement

The first of these unconventional applications to be examined seriously was precise orbit determination (POD) in support of high precision ocean altimetry. A global differential GPS technique for achieving sub-decimeter orbit accuracy on the joint U.S.-French Topex/Poseidon mission was first proposed at the Jet l'repulsion Laboratory in 1981. The basic elements of the proposed differential GPS system--a small global ground network, a precision flight receiver, GPS satellites, and an analysis center—are depicted in Fig. 2. Over the years, a variety of refinements to the orbit estimation technique, evaluated through simulation and covariance analysis, revealed the surprisingly rich potential of GPS for few-centimeter tracking of orbiters at low altitudes [Yunck et al, 1990]. Topex/Poseidon was launched into a 1300 km orbit on an Ariane rocket in August of 1992, carrying an experimental dual frequency P-code receiver built by Motorola to test these new techniques [Melbourne et al, 1994].

The Topex GPS POD demonstration has been highly successful, surpassing pre-launch expectations of 5-10 cm radial orbit accuracy by nearly a factor of three. A number of aspects of this experiment arc notable: (1) conventional dynamic differential GPS orbit solutions were essentially equivalent to dynamic solutions obtained with laser and DORIS (Doppler) tracking data, with radial accuracies of 3-4 cm RMS [Schutz et al, 1994]; (2) reduced dynamic orbit solutions, in which the unique geometric strength of GPS data is used to minimize sensitivity to force model errors [Wu et al, 1991] consistently improved upon dynamic solutions (judged primarily by altimeter crossover agreements) to yield radial orbit accuracies of 2-3 cm RMS [Yunck et al, 1994; Bertiger et al, 1994; Hesper et al, 1994]; (3) University of Texas investigators used GPS data from lopcx/Poseidon to improve the Earth gravity model over what had earlier been achieved by tuning with laser and DORIS data, leading to significantly reduced geographically correlated dynamic orbit error [Bertiger et al, 1994]; [4] dynamic orbits obtained with laser and Doppler data but employing a GPS-tuned gravity model are virtually equal to the GPS reduced dynamic orbits; (5) GPS-based orbits of the highest accuracy are now obtained with a fully automated, unattended processing system; (6) analysis based on Topex results suggests that reduced dynamic orbit accuracies of a few centimeters should be achievable for future missions at altitudes below 500 km [Melbourne et al, 1994; Bertiger et al, 1994]; (7) recent unpublished results by Ron Muellerschoen at JPL indicate that onboard dynamic filtering could yield real time non-differential orbit accuracies of a few meters under nominal levels of selective avai l ability.

Since the Topex receiver cannot decrypt the Y-code, the GPS demonstration has been partially in abeyance since AS came on it January 1994. Routine processing continues, however, with L1 C/A-code, yielding radial accuracies in the range of 4-5 cm RMS, itself a somewhat surprising result. In the wake of the Topex success, GPS-based POD has been adopted for several future altimetry missions, including the U.S. Navy's Geosat Follow-On mission, which will carry a Rockwell MAGR and be launched in 1996, and the Topex/Poseidon Follow-On mission, proposed for launch later in the decade.

GPS Atmospheric occultation

In the late 1980s, a group at JPL proposed observing GPS signals from space as they slice through the earth's atmosphere immediately after rising or before setting, in order to make atmospheric soundings by radio occultation [Yunck and Melbourne, 1989]. Briefly, the observed Doppler shift in the GPS signal induced by atmospheric bending permits accurate estimation of the atmospheric refractive index. From that one can retrieve, in sequence, profiles of the atmospheric density, pressure, and temperature (or, in the lower troposphere, water vapor) with high accuracy (<1 Kelvin in temperature) and a vertical resolution of a few hundred meters [Melbourne et al, 1994b; Kursinski, 1994]. A single satellite can recover more than 500 profiles each day, distributed almost uniformly around the globe; a constellation would recover many thousands of profiles, which could one day have a profound impact on both long term climatological studies and short term weather modeling. In addition, such an array would enable high resolution 3D tomographic imaging of the ionosphere [Hajj et al, 1994] and would serve many geodetic uses [e.g., gravity recovery, geocenter monitoring] as well.

In the early 1990s a group led by the University Corporation for Atmospheric Research in Boulder, CO, succeeded in obtaining sponsorship from the U. S. National Science Foundation for a low-cost demonstration experiment called GPS/MET (for meteorology), to fly as an add-on payload to a NASA experiment (an Optical Transient Detector) aboard Orbital Sciences Corporation's MicroLab I satellite. Additional mission support was provided by NOAA (the National Oceanic and Atmospheric Administration) and the FAA (Federal Aviation Administration), and supplementary analysis support was obtained from NASA. To acquire the occultation data, Allen Osborne Associates, manufacturer of the Turbo Rogue geodetic GPS receiver, developed a ruggedized flight version known as the TurboStar. JPL, a collaborator on the experiment, revamped the receiver software for autonomous operation and occultation scheduling in space. The TurboStar produces 50 Hz dual frequency data samples during occultations using the P-codes when AS is off and alternative methods when AS is on.

The MicroLab I was launched successfully aboard a Pegasus rocket in April 1995. While there have been minor problems with the satellite itself, the receiver has performed flawlessly from the beginning, with no single-event upsets or latchups. Upon power-up, the TurboStar automatically conducts a blind “open sky” search to acquire GPS satellites, uses those to set its internal clock and initialize its orbit solution, computes its Earth-relative position and velocity, schedules hundreds of daily atmospheric occultation passes based on its own computed position, the positions of the GPS satellites, and the known positions of several ground support stations, and feeds a steady stream of data back to the ground. Many hundreds of occultation passes have now been acquired anti analyzed.

The best occultation data are acquired with P-code tracking when AS is off, and JPL has been able to negotiate several AS-off periods, typically a few weeks each, with the Department of Defense. Initial profiles recovered by groups at JPL, UCAR, and the University of Arizona are extremely encouraging, in many cases with estimated accuracies of about 1 Kelvin over a wide range of altitudes [e.g., Hajj et al, 1995]. This performance is expected to improve steadily as analysis refinements are introduced. Ionospheric studies with the GPS/MET data are just now beginning and as yet no results have been reported.

The Future of Spaceborne GPS Science

The success of Earth gravity model tuning on Topex/Poseidon has boosted the prospects of various proposed GPS-based missions devoted to further gravity model improvement. Mission concepts advocated by groups at JPL and GSFC, among other places, include small constellations of independent microsats, each carrying GPS, to refine our knowledge of the long wavelength components of the gravity field, up to about degree and order 25; and pairs of low-orbiting microsats flying in formation on which modified GPS receivers would perform the dual functions of (1) making conventional “high-low” GPS measurements to observe the long-wavelength gravity components, anti (2) making precise “low-low” satellite-satellite range and Doppler measurements (with accuracies of -10 μm and -1 μm/s) to improve the shorter wavelength components up to about degree and order 80. No such mission has been approved.

Several planned international microsat missions will carry versions of the TurboStar for atmospheric occultation and gravity modeling. These include the Danish Ørsted and the South African Sunsat missions, set to be launched together on a Delta rocket in 1997, and a possible Brazilian SACI mission in 1998. in addition, a TurboStar will make occultation observations from the Wakeshield facility, to be deployed and retrieved by the Space Shuttle later in 1995; another will be placed aboard the Russian MIR space station in 1997 for a precise timing experiment in cooperation with the Smithsonian Astrophysical Observatory. At least a half-dozen other TurboStar flights are in the discussion stage.

While the individual occultation missions will serve to advance the GPS technology and validate its capabilities, they will do little for atmospheric science. It is the fervent hope of the growing GPS occultation community that a small pilot constellation of a dozen or so microsats will be sponsored either by government agencies or by commercial interests (eyeing a potential worldwide market in GPS weather products) in the very near future. This could be the prelude to an array of hundreds of tiny, autonomous satellites continuously monitoring the global atmosphere and ionosphere three-dimensionally, with high resolution in space and time (while also improving the gravity model), within a decade. The results from GPS/MET have made the prospect of such a mission tantalizing, and the prospects for its eventual deployment more than promising.

DISCUSSION

GPS is quickly achieving a routinc presence in space for the basic utility functions of real time onboard state determination, precise time and frequency transfer, and moderate precision attitude determinat ion, and is likely to be the n iethod of choice for those tasks for many futurc Earth satellites, both American and international. At present, real time onboard position accuracies fall in the 50-100 m range, limited by the instantaneous effects of SA dither, which typical l y introduces 20-30 m errors in measured pseudorange. Experiments cm EUVE and Topcx/Poseidon (and an earlier simulation study by Bar-Sever et al [1990]) show that robust onboard dynamic filtering can smooth real time position error to a fcw meters, with SA-dither at its nominal level. Similarly, onboard time determination, typically accurate to a few tenths of a microsecond today, can be improved to a few tens of nanoseconds through filtering.

The best current GPS-derived attitude accuracies are reported to be a few tenths of a degree, or about 20 arcmin, with antenna baselines of 1 m. A recent study by Young [1995] suggests that continued improvements in passive and active multipath suppression combined with real t imc dynamic filtering can reduce at tit udc error by more than an order of magnit udc, to about 1 arcmin, with performance ult imatel y limited by the accuracy of the antenna phase center calibration.

Demonstrations of combined GPS/GLONASS in space arc still probably a few years away. While the future of GPS for spaceborne use is secure, it is uncertain at this point whether GPS/GLONASS, with its attendant hardware complications, will gain a foothold in the market.

Spaceborne GPS for Earth science is in the exciting early phase of invention, with promising developments underway in geodesy, climatology, weather modeling, and iono-spheric imaging. The advancement of spaceborne GPS science is rapidly becoming an international venture, with small missions in preparation in a number of countries. These science applications invariably require high performance dual frequency receivers with capabilities well beyond the utility needs of most civilian missions. In the near term there will therefore remain two distinct classes of GPS usc in space. It may one day come to pass, however, that as science advocates progress towards the creation of a large constellation of GPS microsats, the size and cost of high end flight receivers will approach that of utility models, and many more satellites will then be able to contribute to spaceborne GPS science.

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